Characterizations of Electron Beam-Generated Plasmas

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ABSTRACT

Pulsed, electron beam-generated plasmas produced in argon have been characterized using measurements in the bulk plasma and at the plasma/surface interface. A Langmuir probe has been used to measure plasma properties including the electron temperature, plasma density, and plasma potential. At an electrode surface located adjacent to the plasma, the ion flux has been measured and characterized using energy-resolved mass spectrometry. All measurements are resolved in both space and time, leading to a full spatio-temporal description of these plasmas. The results illustrate some of the unique features of electron beam-generated plasmas.

INTRODUCTION

In processes ranging from etching to deposition, knowledge of both the bulk plasma properties and the flux of reactive species at the substrate are important aspects of process quality. Plasma properties such as the electron temperature (T_e) and plasma density (n_p) directly influence the ion flux at surfaces adjacent to the plasma. While the plasma potential (V_p), which is determined by T_e, dictates the ion energies at grounded surfaces, n_p regulates the total number of ions incident to surfaces. Recall that for quasi-neutral plasmas, the electron and ion densities are approximately equal and taken to be synonymous with the plasma density ($n_p=n_e=n_i$). Generally, plasma properties are influenced by the power input, gas pressure, constituent gas species, and by the relative location of electrodes and chamber walls. In terms of process control, it is important to understand the relationship between these properties and input parameters so that a given process can be optimized.

Modulated plasma production [1,2,3], when compared to continuous wave (CW) production adds additional variables that may be used to further enhance process control. In CW production, the plasma achieves a steady state based on the various input parameters. The steady state in pulsed production, if achieved at all, represents only a fraction of the processing time. Over the course of one period, the pulsed plasma exhibits distinct phases, broadly characterized as the initiation, steady state, and afterglow. The evolution of the plasma can lead to unique and useful changes in the flux of species at processing surfaces. For example, the ion-to-radical flux ratio will vary as the plasma progresses through various phases and can be regulated by varying the pulse width or duty ratio.

The Naval Research Laboratory is developing a plasma source based on electron beam ionization [4]. A magnetically confined, multi-keV electron beam is used to ionize a background gas, thus producing a high-density (> 1011 cm^{-3}) plasma over the volume of the beam. There are several features that separate electron beam-generated plasmas from conventional sources (ICP's, ECR's, rf diodes, etc.), most of which are derived from the fact that the electron beam drives the ionization process. First, the plasma production region is limited to the beam volume, which leads to a well-defined and localized source. Second, since the beam electrons are responsible for ionization, there is no need for externally applied electric fields and the plasma electrons are efficiently cooled by inelastic collisions with the background gas. This results in low electron temperatures (T_e < 1.5 eV) [5], which leads to low ion energies at grounded electrodes [6]. Lastly, plasma species production by high-energy electron beams is largely determined by the relative concentrations of the working gas [7]. This is in contrast to most conventional sources where species production favors those with the lowest energy threshold. In its current configuration, the system utilizes a pulsed electron beam, which adds the ability to modulate some of these unique characteristics. The result is a set of properties that can be varied as a function of both time and distance from the electron beam, providing a high level of control over the flux of particles at remotely located substrates.

This paper discusses experiments designed to quantify the spatio-temporal evolution of modulated, electron beam-generated plasmas. The working gas is limited to argon and beam durations extend from 1 to 6 ms. Langmuir probe measurements were used to determine bulk plasma properties. The total ion flux was measured at a grounded electrode located adjacent to the plasma and energy-resolved mass spectroscopy was used to fully analyze the ion flux. Measurements are resolved in both time and space and then reported as a function of pulse width and electron beam-to-electrode distance. The results illustrate the unique features of pulsed, electron beam-generated plasmas and the ability to regulate the flux of ion species in processing applications.

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EXPERIMENTAL APPARATUS

Plasma Chamber and Production

The electron beam source has been operated in a number of chambers [5,6,8] and is transferable between systems without significant differences in operation. With the exceptions of the ion energy measurements, the measurements were performed in the chamber schematically represented in Figure 1. The rectangular plasma chamber is approximately 70-cm long, 25-cm tall, and 100-cm wide (into the page). The chamber base pressure is ~ $1x10^{-8}$ Torr and maintained by a 2000 *l*/s turbomolecular pump. Pure argon (99.999%) was introduced via a mass flow controller at a fixed flow rate of 50 sccm. Operating pressures (30–100 mTorr) were achieved by varying the conductance through a manual gate valve at the entrance to the pump. External to the chamber are magnetic field coils that produce a 150 Gauss field along the center of the chamber that varies by less than 10% over the region of interest.

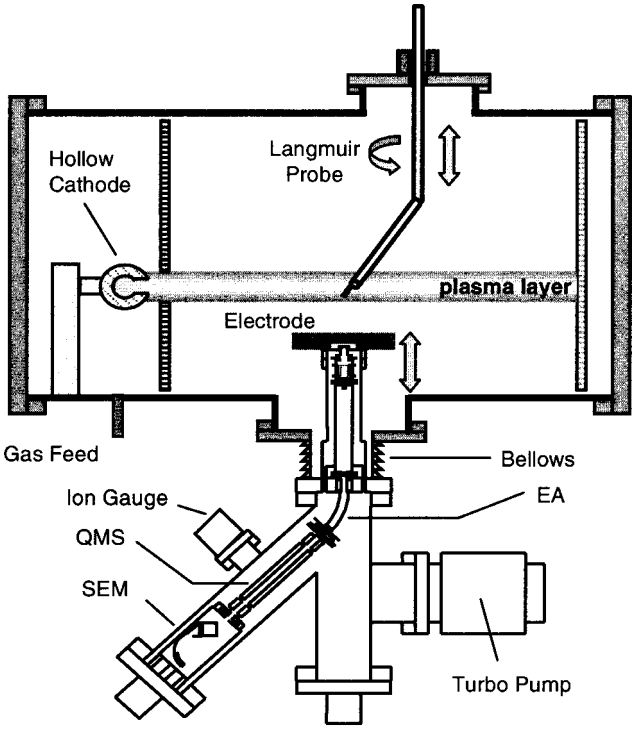

Figure 1: A schematic diagram of the experimental apparatus.

The electron beam was extracted from a linear hollow cathode that was driven by a -2 kV pulse, generating a sheet-like electron beam commensurate with the applied voltage. The emergent beam, collimated by the magnetic field, passed through a slot in a grounded anode located downstream from the hollow cathode and then terminated at a grounded beam dump. The electron beam volume between the slotted anode and dump defines the plasma source, with the dimensions set by the slot size (1 cm x 25 cm) and the anode-to-beam dump length (43 cm). The pulse widths were varied between 1 and 6 ms and the duty ratio was typically, although not limited to, 10%.

Plasma Diagnostics

Ion fluxes and energy distributions were measured at the center of a 5.7-cm-diameter stainless steel electrode using a Hiden EQP 300 Plasma Probe (Figure 1). All electrode distances are referenced to the electron beam edge. The probe is differentially pumped and consists of an electrostatic ion-energy analyzer (EA) in series with a quadrupole mass spectrometer (QMS). Ions enter the EQP through a 50-μm-diameter aperture located in the center of the electrode. The extracted ions are collimated and focused onto the entrance of the energy analyzer by a series of electrostatic lenses. The ions are then energy selected and mass filtered prior to detection by a channeltron secondary-electron multiplier (SEM). The EQP has not been calibrated to determine the absolute flux of each species, and so the intensity of the measured signal is reported in arbitrary units. Time resolution was achieved using both a fixed and scanning gate on the EQP output such that the signal was only accumulated during a given period. For both methods, the signal was accumulated over several hundred pulses to achieve a reasonable signal-to-noise ratio.

The total ion flux was measured at the first focusing lens within the EQP using a current-to-voltage amplifier. The output signal of the amplifier was then recorded on a digital oscilloscope (Lecroy LT344). To maximize the collected current, the first lens was biased to -10 V while the second lens was biased to + 30 V. Simulations suggest that ≈ 10% of the incident ions are collected [9].

T_e, n_p, and V_p were determined using a Langmuir probe as described in Reference [5]. Briefly, the body of the probe was constructed from alumina and stainless steel and contained a nichrome wire heater to maintain a consistent surface. The probe was a 250-μm-diameter tungsten wire, which extended 2 mm from the ceramic housing.

RESULTS AND DISCUSSION

Temporal Dependencies

The Ar^+ energy measurements shown in Figures 2 and 3 have been discussed previously [8]. The ion energy distributions (IEDs) of Figure 2 were collected at a distance of 1 cm. The plasma was produced in 90 mTorr of argon using a 1-ms beam pulse. Shown are IEDs collected over two different periods: Gate A extends from the beginning of the pulse to well into the afterglow (7 ms) and gate B extends from 0.2 to 1.0 ms. Shown in Figure 3 are the energy-resolved flux profiles. Here, the EQP was set in a fixed-energy mode and the flux was accumulated over a 10-ms gate that was scanned in steps of 10 ms. The results of Figure 3 can be directly correlated to the IEDs. The low energy component in the Gate A IEDs results from low energy ions arriving at the electrode during the afterglow. The most probable energies, corresponding to the peak in the IEDs

(≈ 3.5 eV), dominate for the majority of the beam on time. Of additional interest is the presence of higher energy ions that peak early in time.

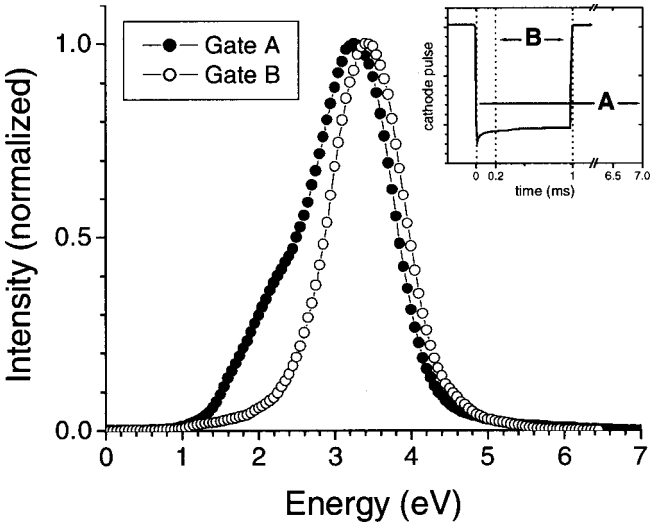

Figure 2: Ar^+ IEDs collected over two time periods (gates) of the pulsed plasma. The periods and cathode driving voltage are shown in the inset.

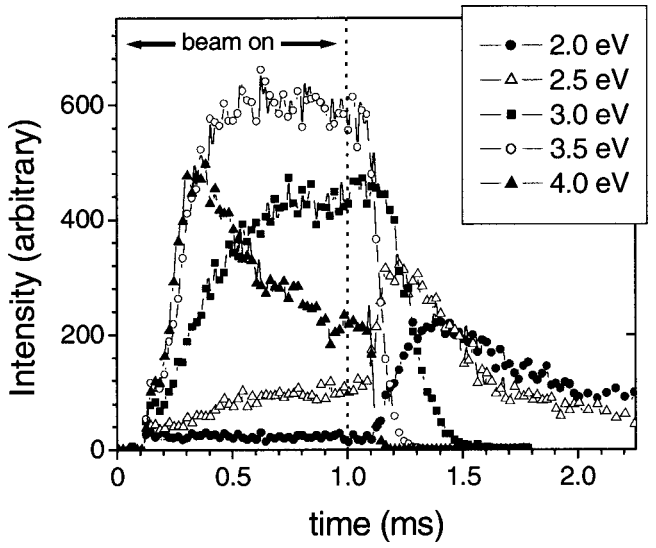

Figure 3: Energy-resolved temporal profiles of the Ar^+ flux.

The total ion flux, primarily Ar^+ (≈ 90 %), is shown in Figure 4. The flux was measured at 2 cm and the total pressure was fixed at 50 mTorr. The results indicate the flux does not reach a steady state until ≈ 4 ms into the pulse. This suggests the measurements of Figures 2 and 3 are not representative of a steady-state plasma. It is reasonable to assume that, if the trends in the energies of Figure 3 would continue, the IEDs in Figure 2 would exhibit a lower most probable energy for longer pulse widths.

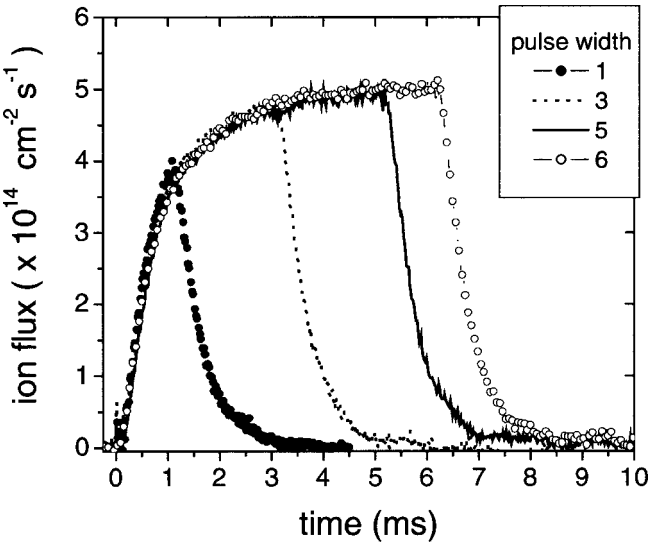

Figure 4: Temporal profiles of the total ion flux for varying plasma pulse widths.

As noted, the flux of species at the electrodes will depend on both T_e and n_p. The measurements of these properties are shown in Figure 5, for a 6-ms pulse in 50 mTorr. Both T_e and n_p are derived from a "best fit" approximation of the probe I-V trace to a Maxwellian electron distribution and the error bars are indicative of the fitting procedure. The electrode was fixed at a distance of 2 cm and the Langmuir probe was positioned on the axis of the electron beam. T_e is high early in the pulse and decreases to near level values before collapsing in the afterglow. The time required to reach the steady-state is largely dependent on the electron cooling mechanism and would appear to be on the order of a few 100 μs. This behavior can be correlated to the incident ion energies; where a high T_e early in time will yield high ion energies while a low T_e in the afterglow results in a low energy flux. The plasma density, on the other hand, exhibits a smooth increase to its steady-state value before collapsing in the afterglow. This behavior correlates well with the ion flux measurements in Figure 4.

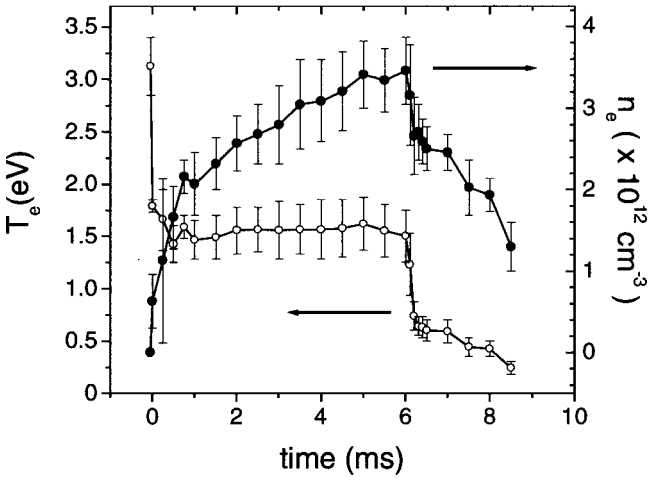

Figure 5: Temporally resolved Langmuir probe measurements.

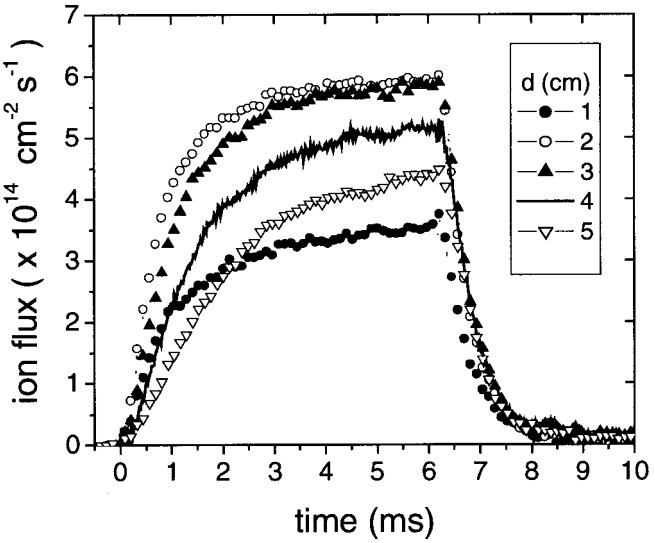

Figure 6: Temporal profiles of the total ion flux at various electrode distances.

The results lead to a simple temporal description of the initiation, steady state, and afterglow phases of plasma generation. The initiation is characterized by high T_e and low n_p that lead to low fluxes of high energy ions. The steady state is characterized by a stable T_e and n_p, producing nearly constant ion energies and fluxes. The steady state value of all parameters should best approximate those found in CW plasma production. The afterglow is characterized by a collapse in T_e and n_p and, thus, a decrease in flux and ion energy. The transition between the initiation and steady-state phases is smooth whereas the transition to the afterglow is abrupt. This behavior is compatible with global models [1], simulations [2], and experimental results [3] for pulsed plasma production using other sources.

Spatial Dependencies

Ion energy distributions measured at increasing electrode distances (not shown) indicate little change in shape but do indicate decreases in the maximum measurable energies. The total ion flux measurements, shown in Figure 6, were measured at variable electrode-beam distances using a constant pulse width of 6 ms. For all spatial profiles, the working pressure was set to 50 mTorr. An interesting result here is that the flux increases for distances up to 2 cm and then decreases for larger distances. It is believed that this behavior is related to the asymmetry in the chamber geometry, which consists of a small electrode located near the plasma layer and an opposing wall located far from the plasma layer (see Figure 1). Preliminary measurements of the on-axis T_e and n_p as a function of electrode distance support this conclusion, showing an increasing density with electrode distance. The difference in times required for the ion flux to reach steady state is related to the diffusion times for the ions to reach the electrode, which is estimated to be 1-3 ms. It is assumed argon plasmas are diffusion dominated, so that wall locations (ion sinks) impact the times required to reach steady state.

Shown in Figures 7 and 8 are the V_p and n_p as a function of distance from the beam axis. For these measurements, the electrode was fixed at 2 cm and the Langmuir probe was scanned along an axis normal to the center of the electrode. All measurements were taken 5-ms into a 6-ms pulse. The data has significant variations but general trends are observable. The asymmetry previously discussed is also apparent in both properties. Nonetheless, a decrease in ion energy and flux with increasing electrode distance can be correlated to a decrease in V_p and n_p with distance from the beam axis.

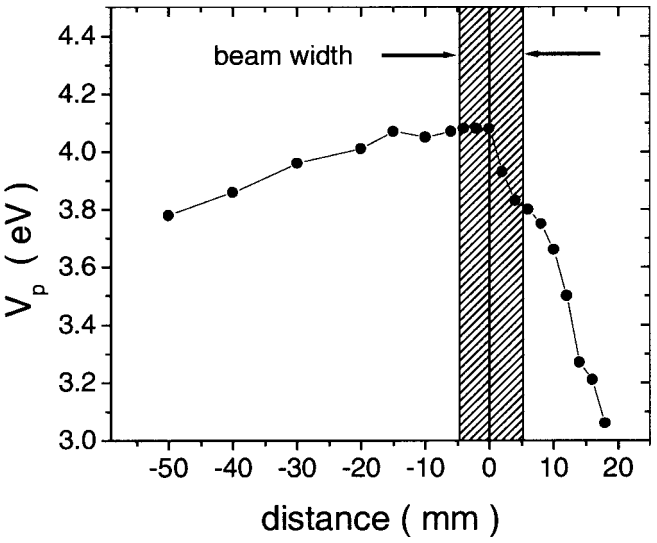

Figure 7: The plasma potential at 5-ms into a 6-ms pulse.

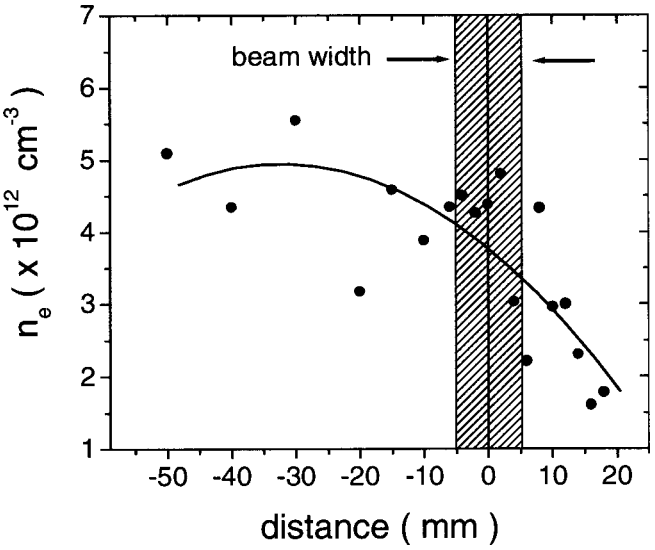

Figure 8: The electron density at 5-ms into a 6-ms pulse.

The spatial characterization indicates the plasma parameters are dependent on the wall locations. Regardless, V_p, and to a lesser extent, n_p, are found to exhibit maximums over or near the beam volume. All parameters tend to decrease in value as the distance from the beam increases. This is comparable to a "flowing afterglow" or "remote" plasma where T_e, n_p, ion energies, and fluxes decrease with distance from the plasma source. With the electron beams in this work, the source region is well localized in space so that the distances from the source region are well defined.

SUMMARY AND CONCLUSIONS

Both Langmuir probe measurements and energy-resolved mass spectrometry have been employed to determine the spatio-temporal characteristics of pulsed, electron beam-generated plasmas produced in argon. Generally, measurements made during the active phase of plasma production indicate steady state electron temperatures are $\approx$ 1.5 eV and plasma densities are ~ 10^{12} cm^{-3} along the beam axis. Average Ar+ energies at a grounded electrode are 3-4 eV and ion fluxes are ~ 10^{14} cm^{-2} s^{-1}. During the initiation, electron temperatures and ion energies are found to be higher, while the plasma density and ion fluxes are found to be lower. In the afterglow, all values are found to decrease as the plasma decays.

The results suggest a unique set of control variables that allow for regulation of ion energies and fluxes at processing surfaces. Adjusting the pulse width and duty cycle as well as the beam-to-surface distance can be used to control the total ion flux. In molecular gases (O_2, N_2, etc.), where the production of reactive neutral species (O, N, etc.) is significant, controlling the ion flux will also lead to a regulation of the ion-to-radical flux ratio. The incident ion energies can also be controlled in a similar fashion. The inherent ion energies in this source are low, and so the small changes in incident ion energy are not particularly relevant to processes requiring high energies. For those applications, increasing the ion energy by applying a bias is straightforward. However, low energies are useful for treating polymers and other less robust substrates.

ACKNOWLEDGMENTS

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